AD-A014 999

EVALUATION OF A PIEZOELECTRIC PUMPING INTERFACE DEVICE

John W. Kelly

United Technologies Corporation

Prepared for:

Army Air Mobility Research and Development Laboratory

August 1974

275100

USAAMRDL-TR- 75-36

ADA014999

EVALUATION OF A PIEZOELECTRIC PUMPING INTERFACE DEVICE

Hamilton Standard Division
United Technologies Corporation
Windsor Locks, Conn. 06096

August 1975

Final Report for Period 1 January 1974 - 31 January 1975

Approved for public release;
distribution unlimited.

Prepared for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
Fort Eustis, Va. 23604

EUSTIS DIRECTORATE POSITION STATEMENT

This report is considered to provide a good description of the design considerations, problems, and limitations associated with the application of high-force piezoelectric devices to gas turbine fuel controls. The information contained in the report and the conclusions cited are considered to be accurate and appropriate to the work conducted. The results will be considered in future planning of any work related to advanced concepts in electronic/mechanical fuel control interfacing.

Mr. Roger G. Furgurson of the Technology Applications Division served as Project Engineer for this effort.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER USAAMRDL-TR-75-36	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EVALUATION OF A PIEZOELECTRIC PUMPING INTERFACE DEVICE		5. TYPE OF REPORT & PERIOD COVERED Final report 1 Jan 1974 - 31 Jan 1975
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John W. Kelly		8. CONTRACT OR GRANT NUMBER(s) DAAJ02-74-C-0024
9. PERFORMING ORGANIZATION NAME AND ADDRESS Hamilton Standard Div., United Technologies Corp. Windsor Locks, Conn. 06096		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62207A 1G262207AH89 01 005 EK
11. CONTROLLING OFFICE NAME AND ADDRESS Eustis Directorate, U.S. Army Air Mobility R&D Laboratory, Fort Eustis, Virginia 23604		12. REPORT DATE August 1975
		13. NUMBER OF PAGES 40
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Gas Turbine Engine Fuel Control

Piezoelectric

Electronic-to-Mechanical Interface

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of a program to design and feasibility test a portion of a turbine engine fuel control system containing a piezoelectric device as the electronic-to-mechanical interface.

The planned program consisted of designing and testing a breadboard of a unique hybrid pumping and metering fuel control. The conceptualized control was powered by a piezoelectric stack and was in a size category for a small gas turbine engine of

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) a slinger nozzle type requiring approximately 700 pounds per hour of fuel at 300 psi. The control utilized the positive displacement pumping action of the piezoelectric powered piston to provide an output flow simulating the requirements for the engine starting mode. The output of an external centrifugal fuel pump for pressurization and simulation of maximum output flow was utilized for the control metering mode operation. Here the piezoelectric actuated piston was operated as a pulse-width modulated metering valve where the percentage of constant frequency pulse train excitation of the piezoelectric stack would define the percentage of maximum output flow.

The hybrid breadboard system was set up for test evaluation on an existing fuel control test facility.

The results of the program are as follows:

It is qualitatively demonstrated that the system could operate in the pumping and metering mode.

Metering mode test data was obtained at room temperature fuel and ambient conditions, and is presented in this report. However, the piezoelectric actuator selected to power the metering piston of the hydromechanical interface failed twice during testing. These failings of the actuator in the breadboard configuration would require additional development effort before a more rigorous demonstration test could proceed to evaluate system performance, repeatability, component reliability, and environmental effects to provide a firm basis for the use of this concept in an advanced control system.

PREFACE

This report covers the evaluation of a piezoelectric pumping interface device as applied to a portion of a gas turbine engine fuel control. The work included the design, fabrication and demonstration testing of a breadboard system.

Acknowledgement is made to the engineering staff of Physics International Company, San Leandro, California, for their assistance in this program.

The program was conducted at the Hamilton Standard Division of United Technologies Corporation, Windsor Locks, Connecticut.

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INTRODUCTION

The increase in the application of digital electronics to gas turbine engine controls creates the need for improvements in the direct digital electronic-to-mechanical interface devices. A piezoelectric device potentially offers this capability for fast-response digital electronic-to-mechanical conversion.

The purpose of this program was to design, fabricate and feasibility test a portion of a gas turbine fuel control system containing a piezoelectric actuator/pumping interface.

The approach taken in the work performed in this program was as follows:

Phase I Design

A breadboard type fuel metering system was designed. The system and elements chosen were as follows:

- A hydraulic control package consisting of a metering piston/valve, a pressure regulating valve, and inlet and discharge check valves contained in a suitable housing was designed. Flow levels were compatible with small turbine engines, of the slinger nozzle type, i.e., a fuel flow of approximately 700 pounds per hour at a maximum of 300 psig. Fuel flow was provided from an external centrifugal pump.

- A piezoelectric actuator was specified for procurement. This actuator, basically a stack of piezoelectric discs expanding in proportion to an applied voltage and hydraulically amplified for low force-large displacement output, was designed to power the metering piston of the hydraulic package.

- The electronic output requirement for the piezoelectric actuator pulser was defined for procurement. This electronic unit provided a means of examining interface and system operation over a range of frequencies and pulse widths by manual input.

Phase II Component Fabrication and Test

Manufacture and procurement of breadboard hardware defined in Phase I was accomplished.

Component testing upon completion of manufacture/procurement was initiated and completed.

- The pressure regulating valve was tested to establish accuracy and droop characteristics.

- The check valves were tested for leakage, cracking pressure and suitability for the demonstration system.

- The piezoelectric actuator was evaluated to determine its operating characteristics, output force and displacement.

- The metering piston was evaluated for adequacy in the demonstration system.

Phase III <u>System Test</u>

The assembled breadboard unit was tested at room temperature fuel and ambient conditions in a facility with an external centrifugal fuel supply source. This phase of the program could not be completed in the time frame of the contract. Two failures of the piezoelectric actuator prevented evaluation and verification of the system performance at the fuel and ambient ranges of MIL-E-8593. Some room temperature fuel and ambient test data was obtained in the metering mode, and qualitative data was obtained in the pumping mode. The data is presented in this report.

Phase IV <u>Analysis and Preliminary Design</u>

This phase was planned but not completed since further work to demonstrate and determine the system characteristics is required.

DESCRIPTION OF THE DEMONSTRATION HARDWARE AND CONCEPT

The concept of the breadboard fuel control demonstrator is shown schematically in Figure 1. Fuel flow is provided from an external centrifugal pump. The hydraulic package and the piezoelectric actuator elements are shown within the broken lines. The hydraulic package is comprised of a metering piston/valve, a pressure regulating valve and two check valves. The piezoelectric actuator is comprized of the crystal stack, check valve and sealed amplifying chamber and output plunger.

The breadboard system was designed to provide flow in two modes: pumping and metering.

- Pumping - In this mode, simulating an engine starting operation, the pressure regulating valve would be saturated open due to insufficient centrifugal pump delivery pressure. Output fuel flow would be in proportion to the cyclic rate of the metering piston/valve displacement volume as driven by the piezoelectric actuator.

- Metering - In this mode, simulating an engine operating between idle and maximum speed, the output pressure of the centrifugal pump is sufficient to cause the system, in conjunction with the pressure regulating valve and metering valve window, to provide maximum output flow as long as the piezoelectric actuator is not being energized. If the actuator is energized, the output plunger drives the metering piston/valve closed and output flow drops to zero. Therefore, output flow can be pulse width modulated; i.e., at constant frequency, the valve, if open 10% of cycle duration, would result in an average fuel flow of 10% of maximum.

The electronics to drive the demonstrator piezoelectric actuator provided a means of manually varying and establishing frequencies and pulse widths in both the pumping and metering modes. Implementation of computer controlled pulse width variation and mode switching to simulate operation with an engine was not provided.

DESIGN SUMMARY

The breadboard demonstrator assembly is shown in the photograph of Figure 2. Cross sections through the unit are shown in Figure 3. The fuel flow path through the pressure regulating valve and inlet check valve to the metering window is shown in section B-B, while the flow path through the metering valve and output check valve is shown in section C-C. The piezoelectric drive plunger and proximity displacement transducer assembly are also shown in section C-C. An exploded view of the hydraulic package is presented in Figure 4. Here a mechanical drive has replaced the piezoelectric actuator and a plug has replaced the proximity device. This configuration was established for ease of component testing.

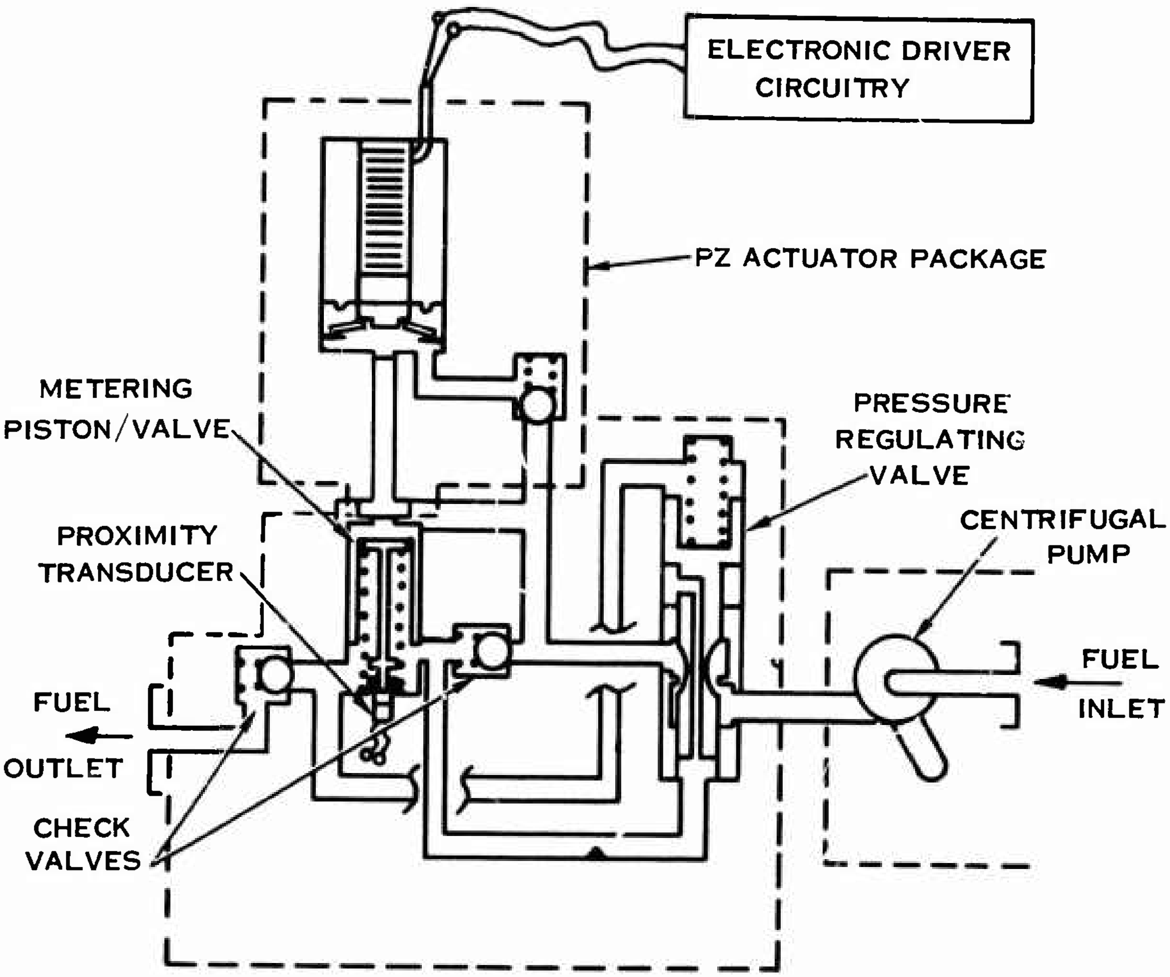

Figure 1. Piezoelectric Pumping Interface Fuel Control Schematic

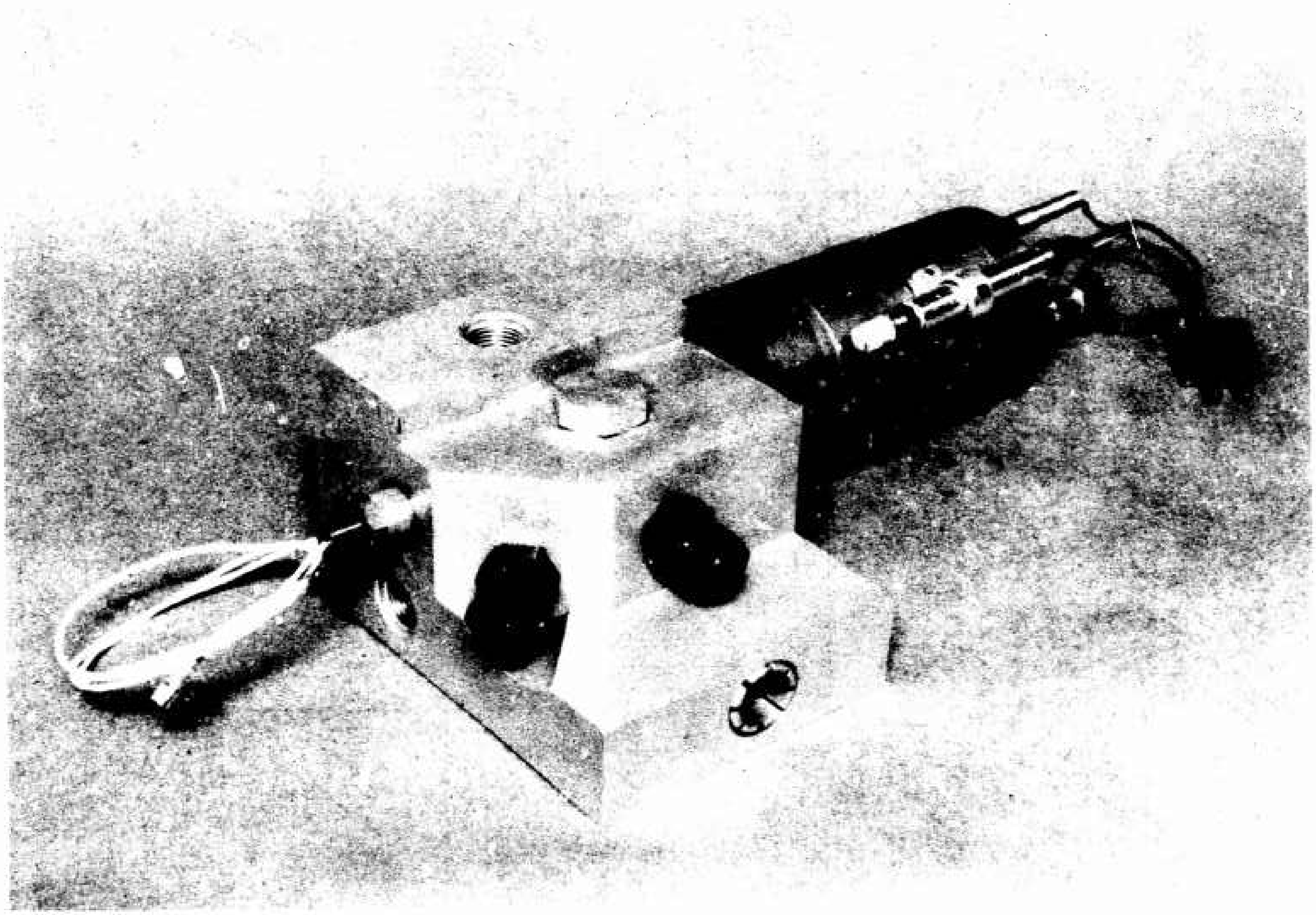

Figure 2. Piezoelectric Breadboard Demonstrator Assembly

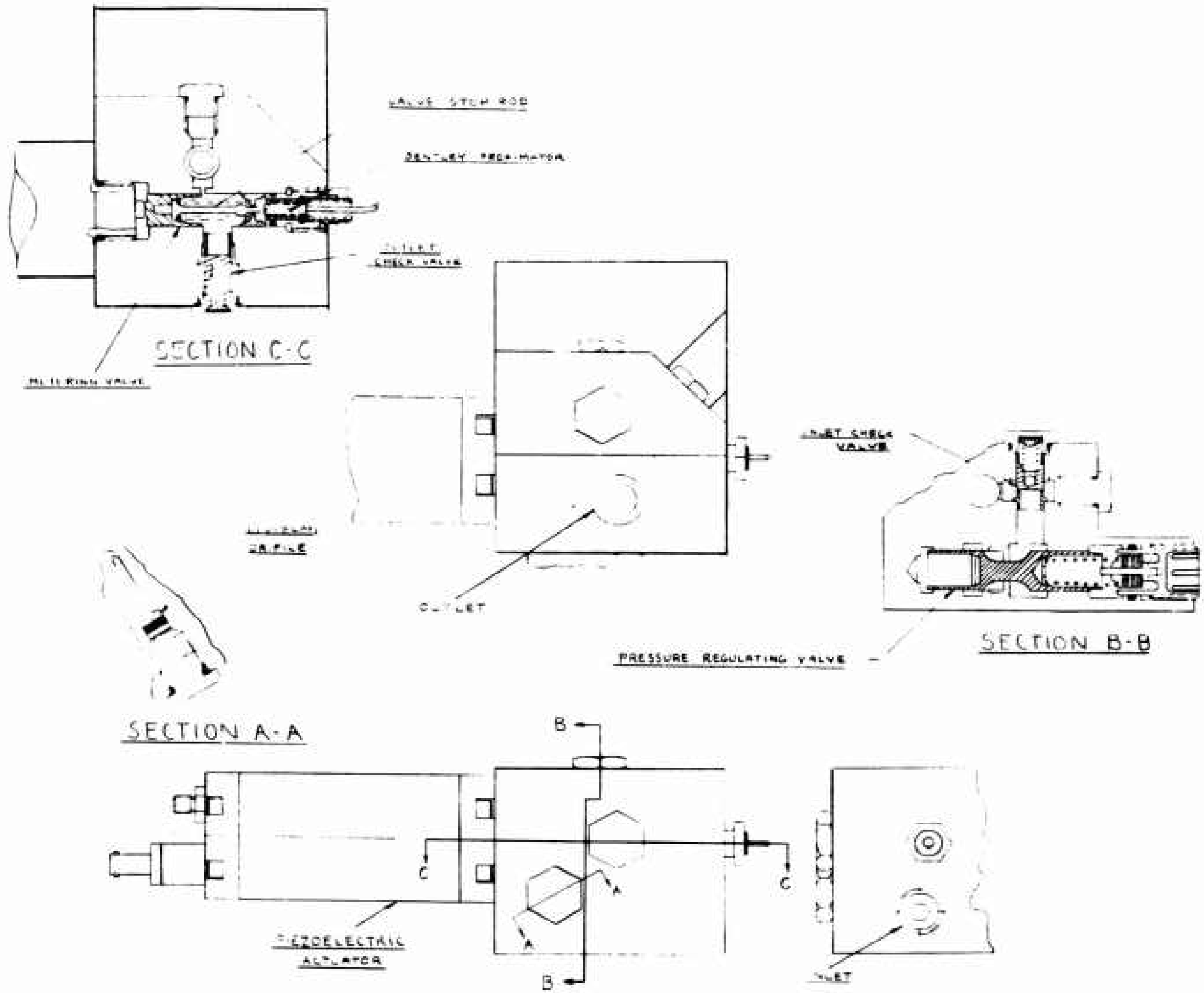

Figure 3. Piezoelectric Interface Demonstrator

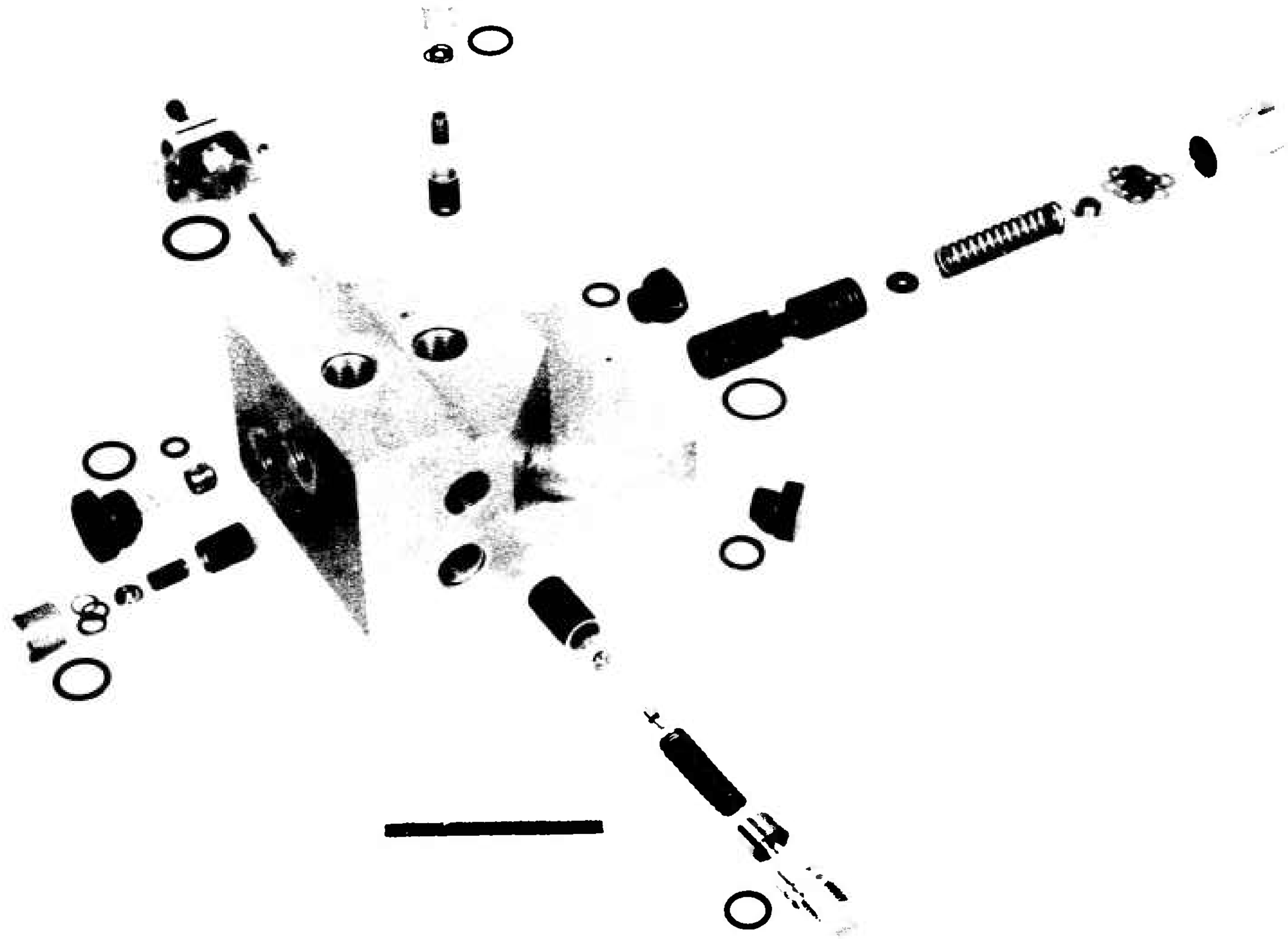

Figure 4. Breadboard Hydraulic Package, Exploded View

Pertinent dimensional and design data for the metering pump/valve, check valve and pressure regulating valve are presented in Table 1.

PIEZOELECTRIC DEVICES

Piezoelectric devices employ ceramic material with some degree of motion amplification. The piezoceramic drivers are high-force low-displacement devices, and their successful application demands careful attention to coupling. Piezoelectric materials exist in nature (e.g., Quartz, Rochele salt) and as man-made formulations (e.g., barium titanate, lead zirconate titanate). These materials exhibit strong coupling between electrical and mechanical properties because of an asymmetry in crystal structure. The application of an electric field along one axis of a polycrystalline disc of piezoelectric material (PZ) biases the crystals to align their longest axis with the direction of the field. Since many crystals are involved, the alignment is statistically influenced and the strain/field response tends to be linear rather than by step function. Barium titanate and lead zirconate titanate have shown that normal unrestricted strains of 0.002 in./in. are developed with applied field strengths of 50 KV/in. Thin discs permit the use of a high electric field gradient with low applied voltage. When a dc voltage is applied across the disc, the material develops a strain in the direction of application of the electric field. If a number of these discs are stacked with thin metal electrodes between adjacent faces and if electrical connection is made to energize all the discs in parallel, small displacements of each disc are aggregated and force may be applied axially. A stack of piezoelectric discs, therefore, constitutes a driver that can generate a high force intensity with a displacement of several thousandths of an inch. Figure 5 shows schematically the disc arrangement and means of amplifying the resultant motion.

DEMONSTRATOR PIEZOELECTRIC ACTUATOR

The design input-output characteristics for the demonstrator piezoelectric actuator are given in Table 2. The actuator was procured from the Physics International Company, San Leandro, California.

The actuator in the drawing of Figure 6 is comprised of 86 piezoelectric discs fabricated by the Physics International Company. These discs are 1.25 inches in diameter by 0.040 inch thick, connected electrically in parallel. The movement of the stack is amplified 30 times by the combination of a 1.25-inch-diameter diaphragm hydraulically coupled to a 0.228-inch-diameter plunger. The seal between the fuel and the housing and plunger rod is formed by a very close clearance fit of 0.000080 to 0.00012 inch. This forms a low-friction seal and allows leakage of fluid necessary to compensate for thermal expansion of the fluid. Some leakage also occurs during constant temperature operation. To compensate, makeup fluid enters the amplifying chamber through a small check valve (187

TABLE 1. PIEZOELECTRIC PUMPING INTERFACE DESIGN SUMMARY

Metering Pump Valve	
Diameter	0.625 in. nominal
Stroke	0.040 in. nominal
Spring Load - Window Open	26 to 30 lb
Window Closed	32 to 35 lb
Spring Rate	125 lb/in. nominal
Pumping Mode	
Pumping Frequency	0 to 100 pulses per second (pps)
Minimum Output Flow	1.00 in.^{3}/sec @ 100 pps
Metering Mode	
Frequency	20 to 40 pps
Metered Flow Range	100 to 700 pounds per hour (pph) @ 40 psid
Leakage-Window Closed	78 pph @ 40 psid
Check Valves	
Diameter	0.405 in. nominal
Stroke	Stop at 0.030 in. stroke
Spring Load Closed	0.64 lb shimmed
Spring Rate	44 lb/in. nominal
Cracking Pressure	5 psi nominal
Pressure Drop	10 psid @ 700 pph
Leakage	0.05 in.^{3}/sec @ 8.5 psid
Pressure Regulating Valve (PRV)	
Diameter	0.750 in. nominal
Stroke	0.050 in.
Spring Load	17 lb @ line-on-line
Spring Rate	20 lb/in. nominal
PRV Pressure Drop	30 to 220 psid
Regulated Pressure	40 psi nominal
Valve Droop	2.2 psid nominal
Leakage at Line-on-Line	48 pph

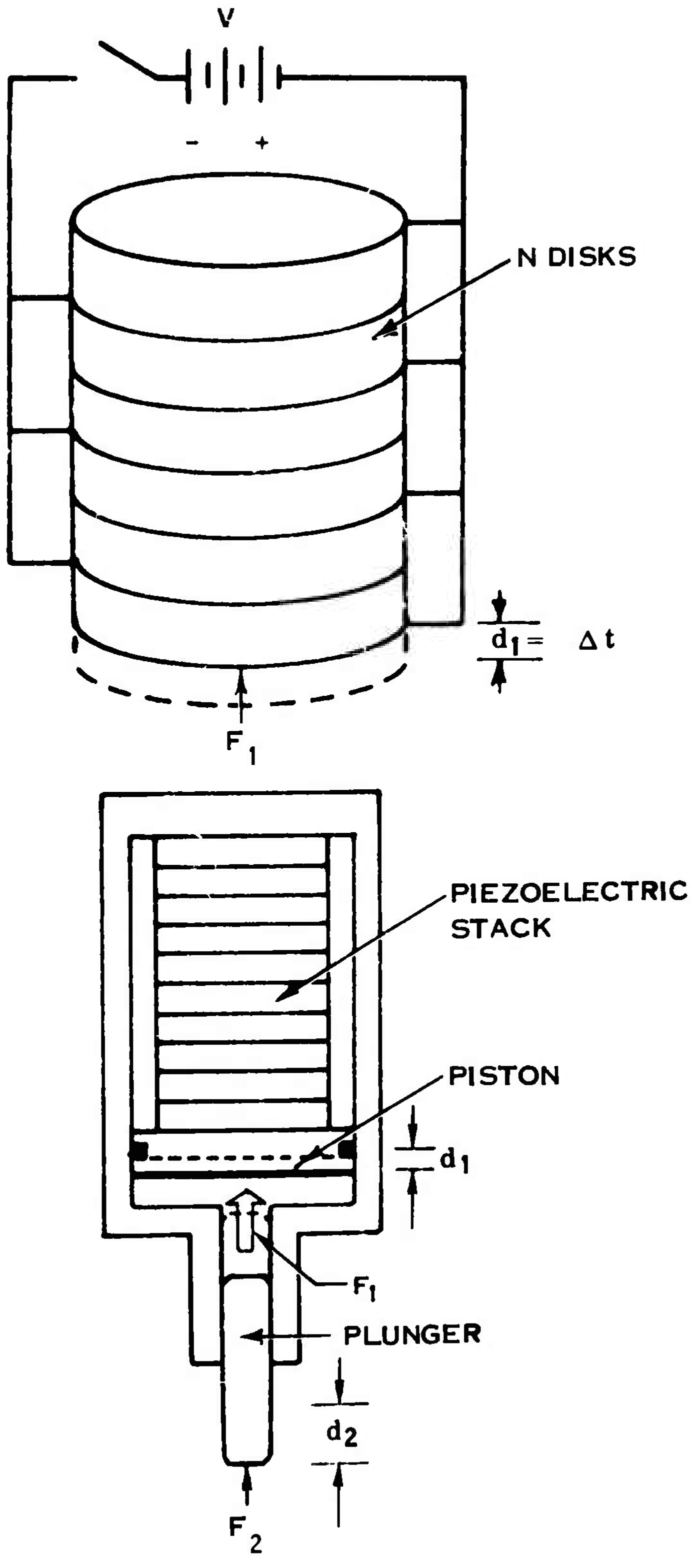

Figure 5. Basic Piezoelectric Energy Converter

TABLE II. PIEZOELECTRIC ACTUATOR DESIGN SUMMARY

Input	
Input Voltage	0-to +1200
Rise and Fail Time	500 μsec minimum
Pulse Frequency	
Pumping	150 pps maximum
Metering	20 to 40 pps
PZ Stack Capacitance	2.3 μf
Pulse Width	1 to 48 ms
Input Power	75 to 100 watts
Output	
Plunger Movement (at 1200 volts and no force)	0.075 in.
Normal Operating Plunger Movement (0 to a positive stop)	0.0375 in.
Force (at 1200 volts and 0.0375 inch stroke)	40 lb
Stall Force (at 1200 volts and no movement)	80 lb
Plunger Weight (approx.)	0.015 lb
Response Time	< 1 ms
Life (Design Goal)	
High Temperature (after an 8-hr soak)	
Fuel	+135°F
Ambient	+160°F
Cycles	1.1×10^6 at 40 pps 1.8×10^6 at 100 pps
Room Temperature	
Fuel	+100°F
Ambient	+90°F
Cycles	6.5×10^6 at pps 3.6×10^5 at 100 pps

TABLE 2 (Cont)	
Simulated Starts (After a 72-hr -65°F cold soak)	
Fuel	-65°F
Ambient	-65°F
Cycles	1.1×10^5 at 30 pps
	3.6×10^5 at 100 pps
	4.3×10^5 at 70 pps

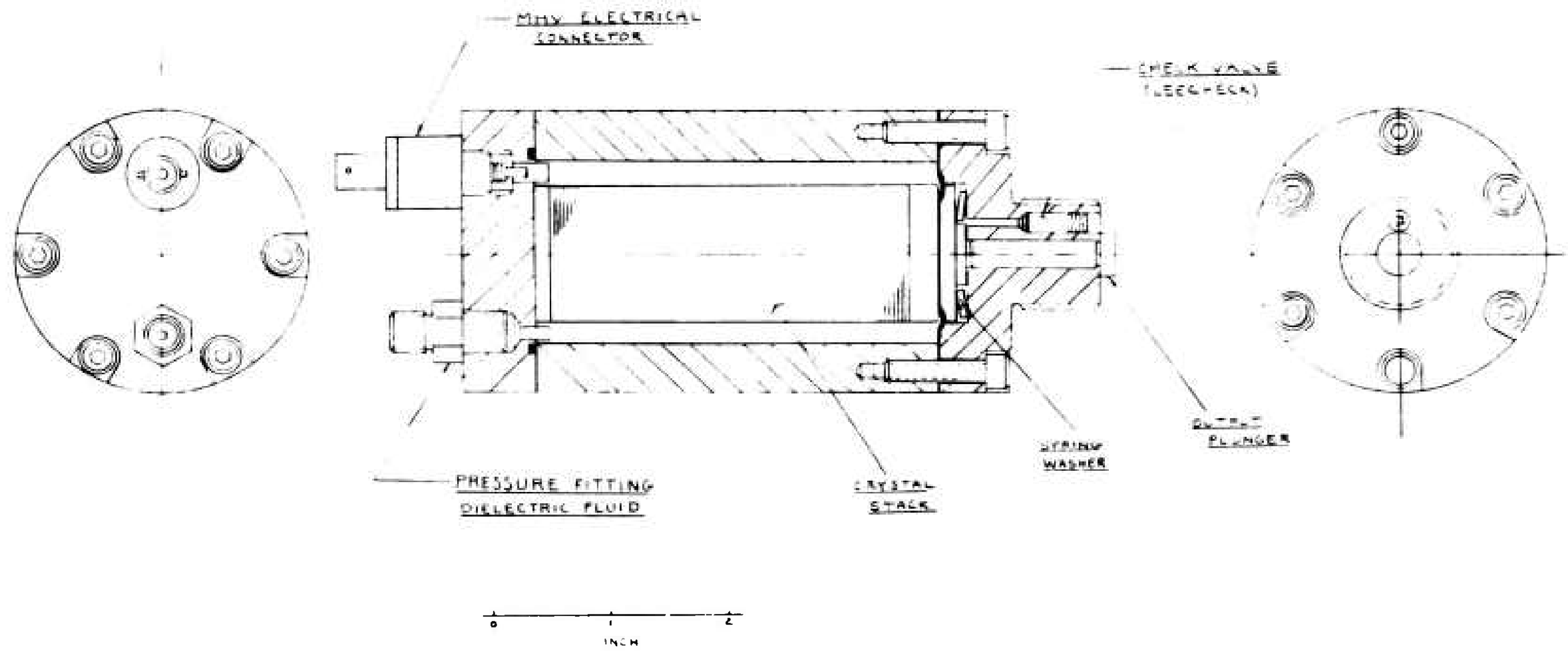

Figure 6. Piezoelectric Actuator Assembly

Leecheck). Because of the makeup requirement, the actuator must operate in a pulsed rather than a constant voltage mode. The actuator relies on the energy generated in the metering piston/valve spring to return the plunger rapidly to its stop in the zero voltage condition. The metering piston/valve and spring are constrained to operate between the limits of the actuator housing plunger stop and the stop rod provided in the hydraulic housing of the demonstrator. The space around the PZ stack is filled with Dow Corning DC-200 dielectric fluid to permit operation in high electric fields. It is assumed ultimately that this can either be eliminated or replaced with fuel.

ELECTRONIC PULSER

Table 3 presents the required performance for an electronic pulser to provide a means of examining breadboard control operation. The schematic of the electronics is shown in Figure 7. A console type electronic pulser and power supply was procured from the Physics International Company.

SYSTEM PERFORMANCE

Figures 8 and 9 present the predicted system performance of the demonstrator assembly. Figure 8 defines the estimated pumping mode performance, and Figure 9 defines the estimated metering mode performance. Estimated metering piston/valve response to a 100-pps input is shown in Figure 10.

TABLE 3. PERFORMANCE OF PIEZOELECTRIC PUMPING INTERFACE DEMONSTRATOR PULSER

Pumping	
Voltage	0-1200 volts
Frequency	Adjustable between 20 and 100 pps
Pulse Width	Adjustable between 2 and 5 ms
Rise and Fall Time	500 μ sec to 1 ms
Metering	
Voltage	0-1200 volts
Frequency	Adjustable between 20 and 40 pps
Pulse Width	Adjustable between 2 and 48 ms
Rise and Fall Time	500 μ sec to 1 ms

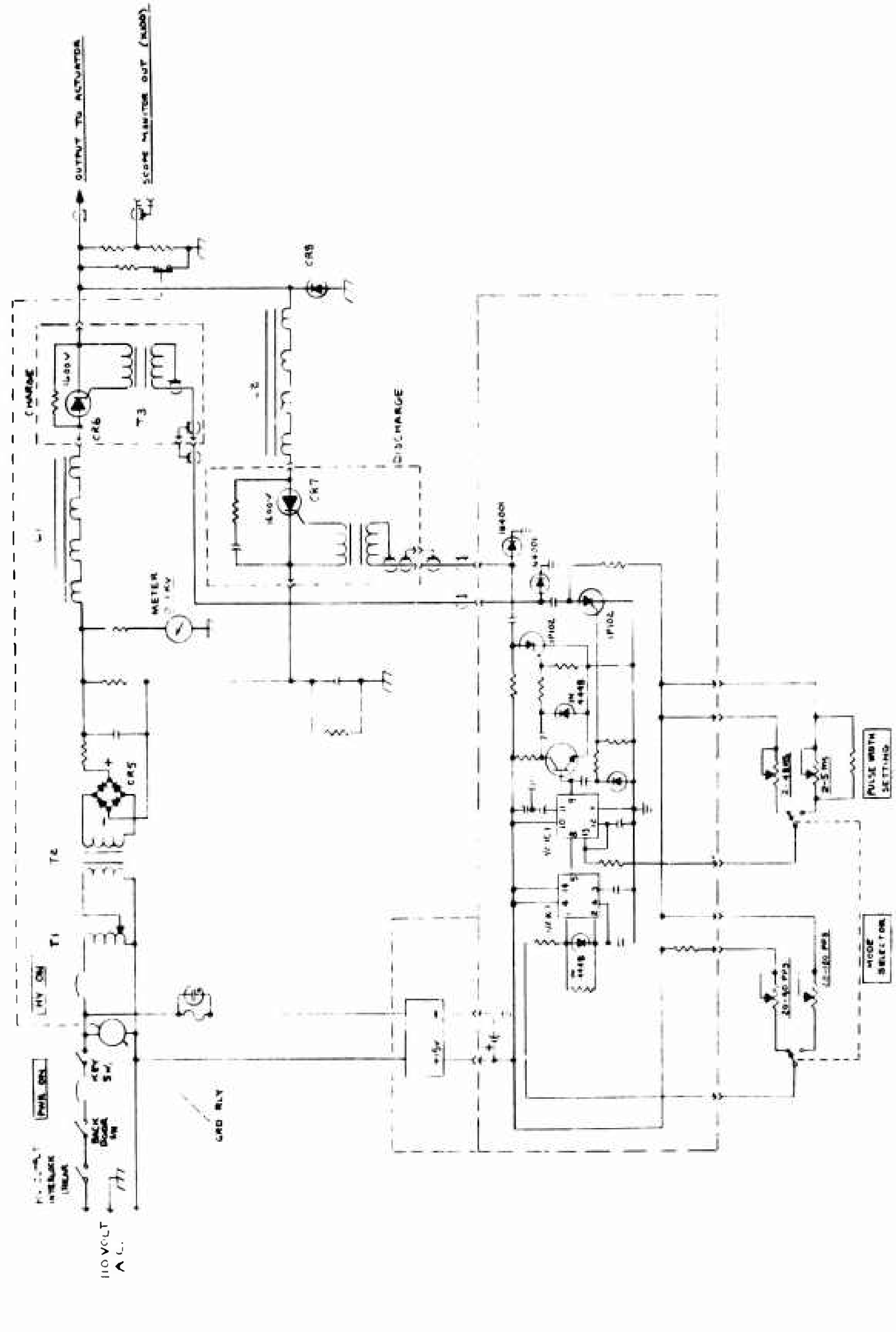

Figure 7. Electronic Pulser and Power Supply Schematic

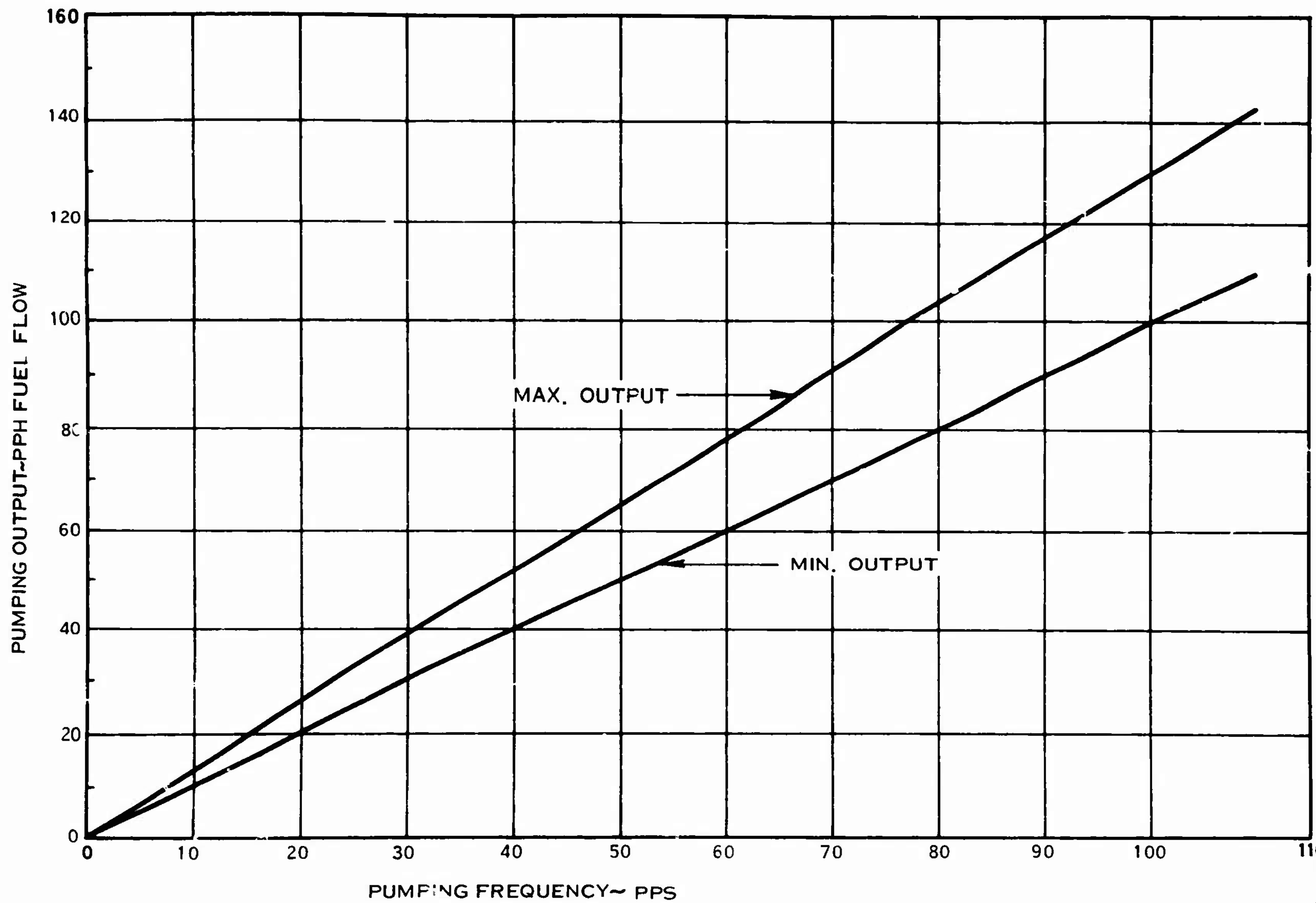

Figure 8. Estimated Pumping Mode Performance

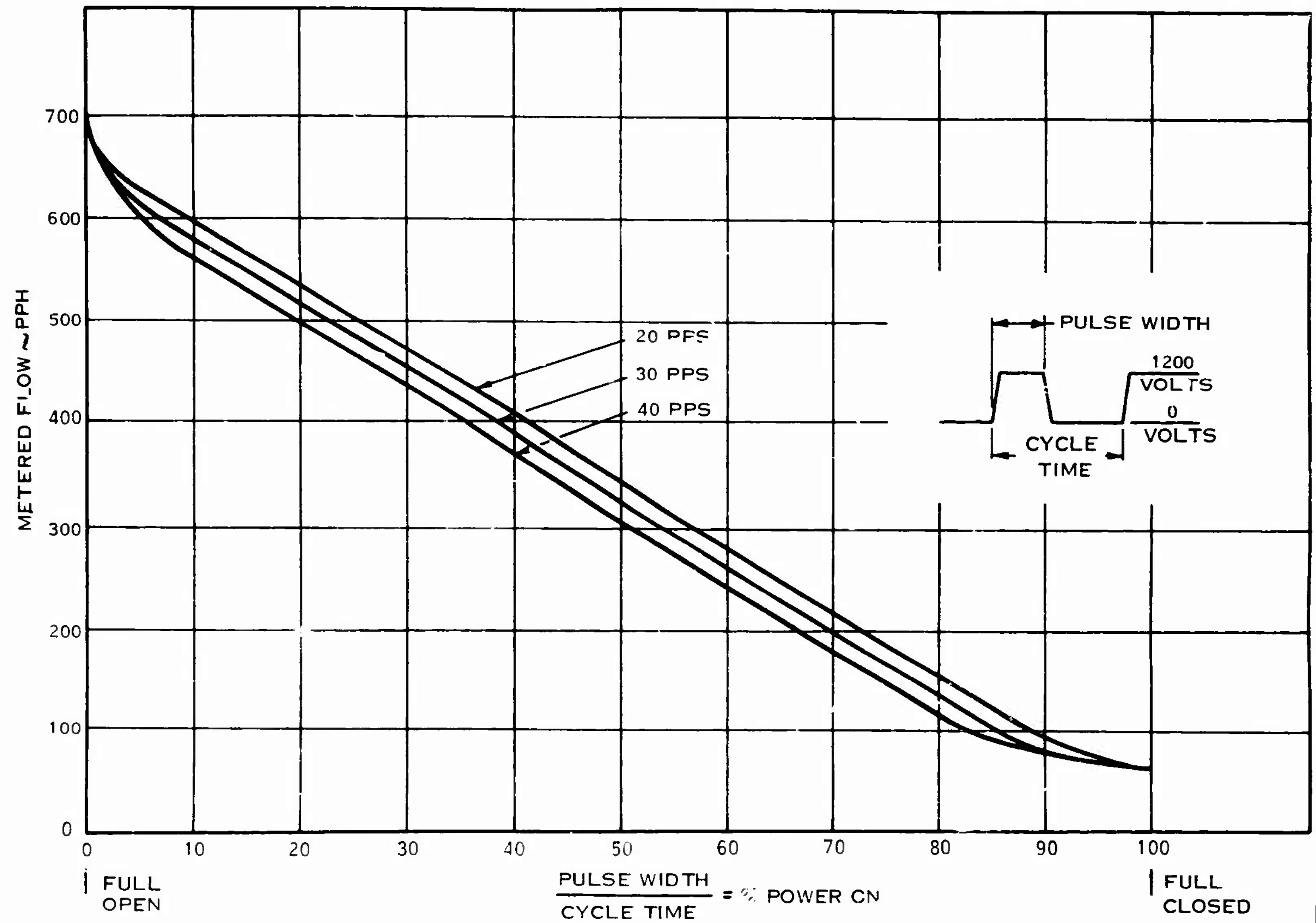

Figure 9. Estimated Metering Mode Performance

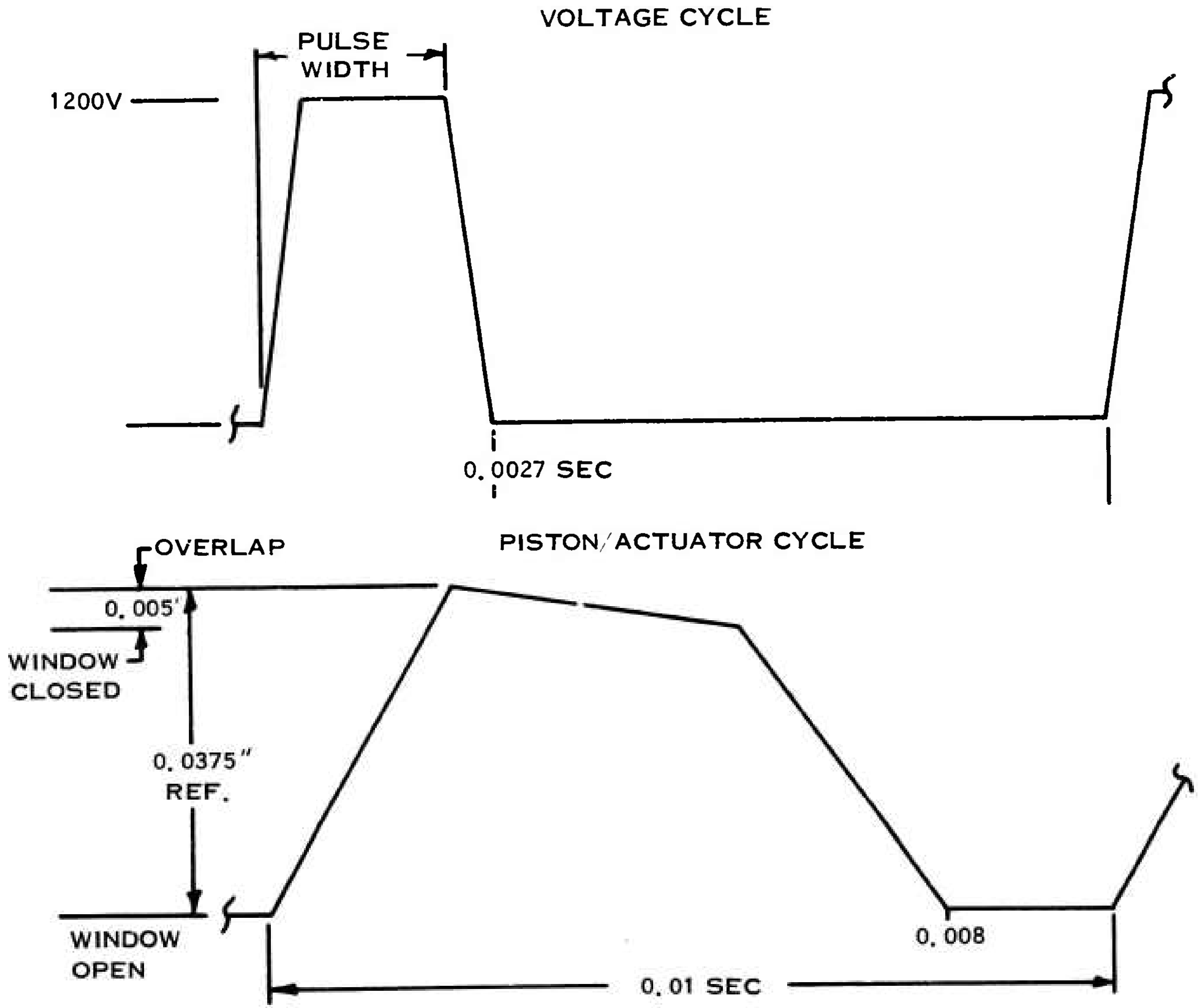

Figure 10. Estimated Metering Piston Response at 100 pps

TEST FACILITY

A test facility was provided on an existing fuel control test rig. The rig was modified to add the necessary features for operation of a high-voltage device in a fuel area and provide lockout devices for personnel protection.

The basic rig provided the drive and fuel supply boost system for a centrifugal fuel pump. The pump used was one developed for a missile fuel control system. The pump setup for these tests produced a minimum of 1000 pounds per hour of fuel at 300 psig discharge pressure to the test unit. Rig boost provided 20-50 psig at the pump inlet. Drive speed could be varied over 4000 - 40400 rpm. The rig system provided temperature capability from -65°F to +135°F.

The Plexiglas chamber provided the ambient capability of -65°F to +160°F and also the N2 purge and voltage lockout. A positive N2 pressure was required to permit system operation. Loss of N2 pressure shut down the voltage input to the piezoelectric actuator and shorted the stack to ground to remove the capacitive residual charge. A schematic representation of the system is presented in Figure 11, and a photograph of the test setup is given in Figure 12.

Instrumentation

The instrumentation to evaluate the operation of the piezoelectric interface system is shown in Figure 13. The instrumentation was set up such that a visicorder recording oscillograph could be used to record system input-outputs. The electronic pulser console to provide input frequency excitation and pulse-width control is shown at the right. Thus, with the fuel system at operational pressures and maximum flow, the input pulse width could be established at the desired frequency and monitored on the oscilloscope of the center conditioning equipment console. The output of the demonstrator metering piston obtained from the installed Bently Proximator Transducer was displayed on the oscilloscope. As desired, then, this data could be recorded on the visicorder along with desired input and output pressure and fuel flow. In the pumping mode, rig boost could be varied to provide input pressure, without centrifugal pump operation, to the breadboard control. All other parameters could be recorded and established as in the metering mode. A back-pressure valve is provided in the output line to adjust control back pressure.

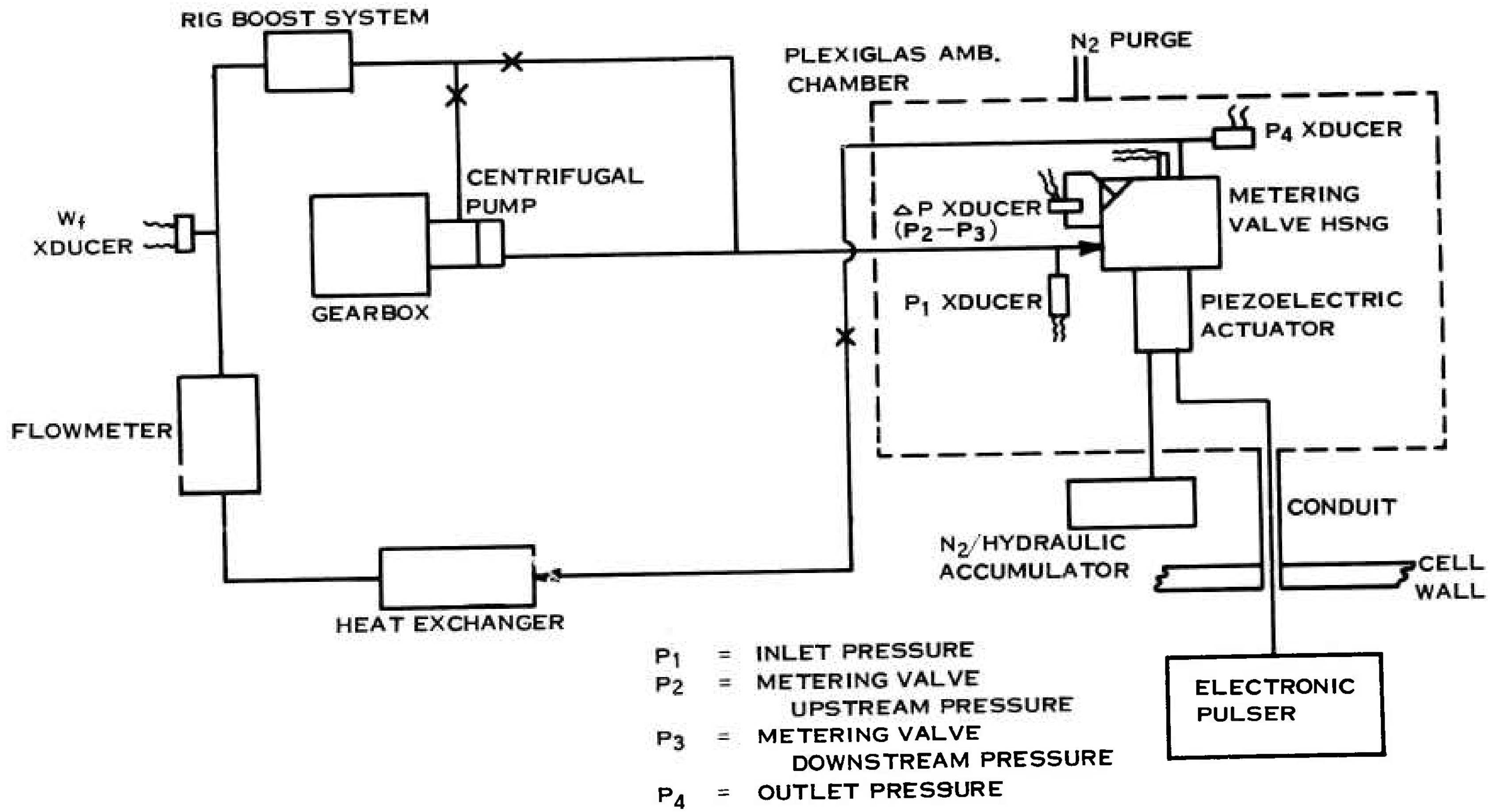

Figure 11. Demonstrator Engine Control Test Rig Schematic

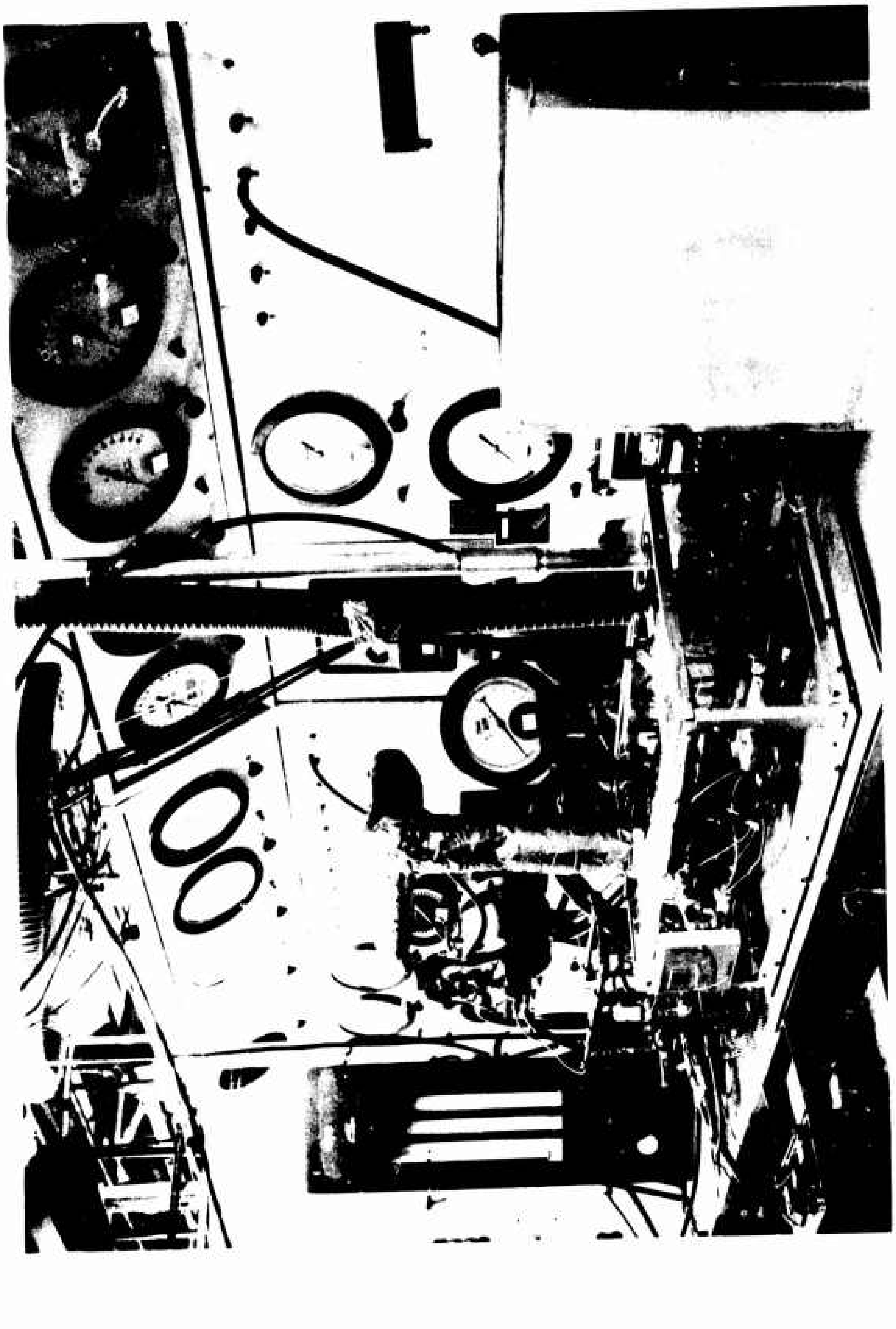

Figure 12. Experimental Test Rig

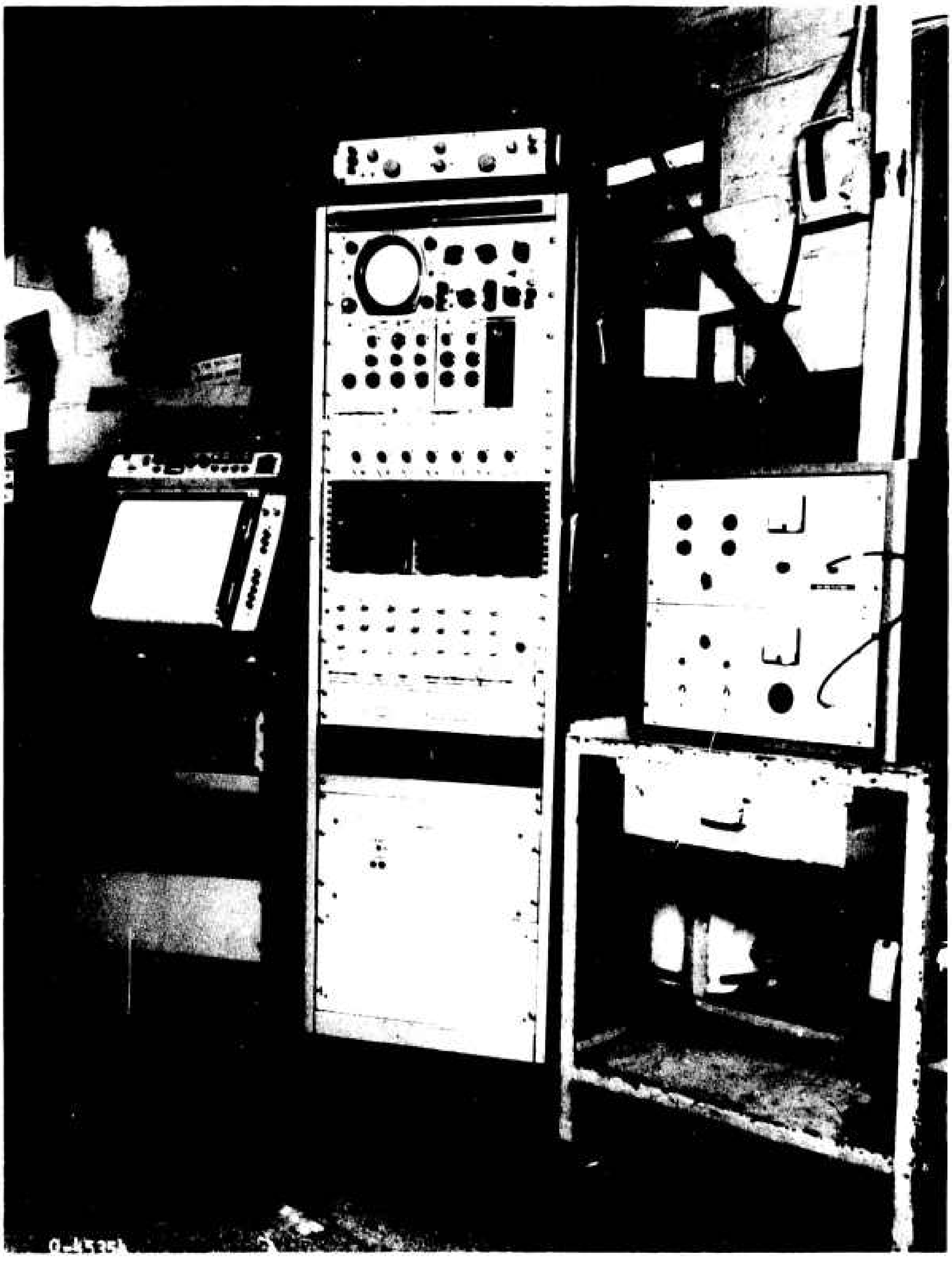

Figure 13. Experimental Test Rig Instrumentation

TEST RESULTS AND DISCUSSION

Phase II - Component Tests

The objective of these tests was to obtain performance data for the hydraulic package elements and the piezoelectric actuator as components prior to their use in system testing of Phase III. The results of these tests are as follows:

Pressure Regulating Valve

A plot of pressure regulating valve data is shown on Figure 14. The data indicated suitability for use in the demonstrator and met design predictions. All testing was accomplished in the demonstrator housing.

Check Valves

The inlet and outlet check valves were tested for valve seating capability, adjusted for cracking pressure by appropriate shimming and flow pressure drop. Table 4 presents the results of those tests. All tests were conducted in the demonstrator housing. As noted, design pressure drop was lower than actually recorded. It was felt that this was due to the method of test using the basic housing and passage plugs. Valve seats were pressed in the main housing. The test results indicate suitability for systems evaluation.

TABLE 4. CHECK VALVE TEST DATA

	INLET		OUTLET	
	Actual	Design	Actual	Design
Cracking Pressure (psid)	5.6	5.0	5.2	5.0
Pressure Drop (psid @ 700 pph)	12.3	10.0	14.3	10.0
Leakage (in.^{3}/sec @ 8.5 psid)	0.005	0.05	0.002	0.05

Metering Piston

The metering piston was evaluated in the assembly to determine fuel flow in the closed and open position with a 40-psid delta P across the metering window.

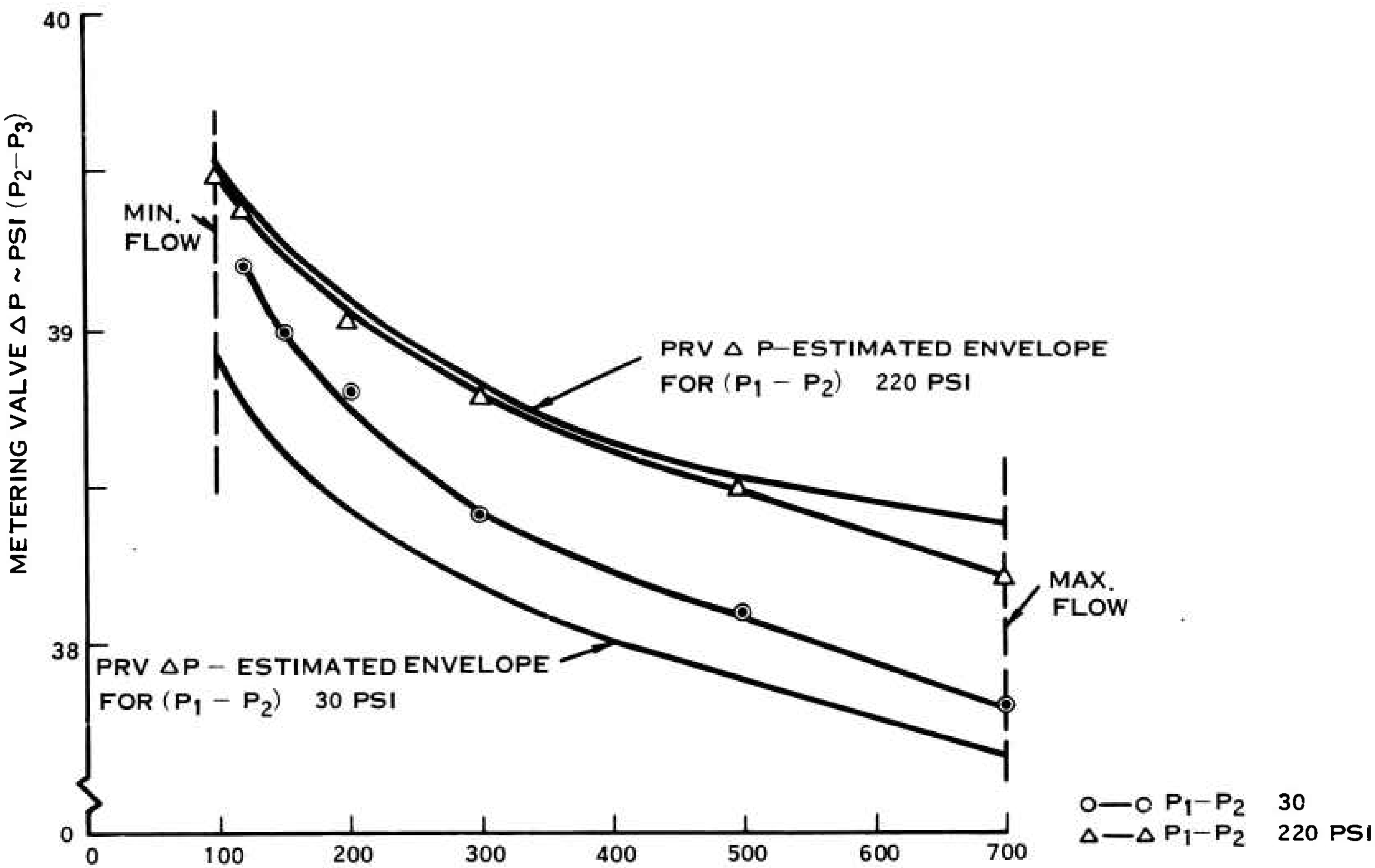

Figure 14. Pressure Regulating Valve (PRV) Component Performance

Table 5 shows a tabulation of the data obtained. As noted, the flow is higher than design predictions, and is felt to be due to the estimated value for the coefficient of discharge. A value of 0.5 was used in design, where the test results would indicate a value of 0.7. The force level for valve position was within design prediction and was within the capability of the piezoelectric actuator to produce.

TABLE 5. METERING VALVE TEST DATA

	FLOW-PPH		FORCE-LB	
	Actual	Design	Actual	Design
Closed (0.005 in. overlap)	110	78	32	31-35
Open (0.040 in. travel)	940	700	26	26-30

Piezoelectric Actuator

Tests were conducted on the actuator as a component prior to the first installation and systems test with the hydraulic package. The data obtained is presented in Figures 15 and 16. Figure 15 presents the reduced data for output plunger displacement vs plunger force at a voltage level of 1200 vdc. The characteristic is compared to the desired design, shown dashed. The difference is attributed to leakage through the output plunger clearance during constant-voltage operation. This should not occur during pulsed operation. Figure 16 presents typical 60-Hz sinusoidal response of output plunger vs input voltage. Total voltage variation was 1200 volts. The actuator drove the plunger against a simulated piston and spring of the design spring rate with the preload set at 35 pounds. The results of those tests indicated that the actuator was suitable for installation and further systems tests with the hydraulic package.

A discussion of the subsequent two actuator failures is presented under Phase III Test Results.

Phase III - Systems Tests

The objective of the Phase III tests was to demonstrate the operation of the breadboard control in the pumping mode and in the metering mode at room temperature fuel and ambient conditions and at the extremes of the fuel and ambient conditions as defined in MIL-E-8593.

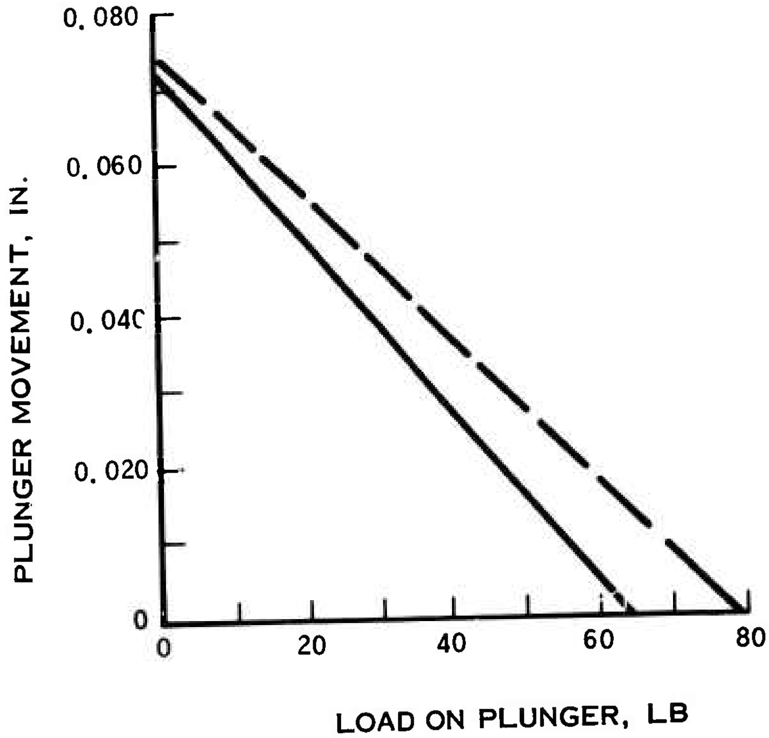

Figure 15. Piesoelectric Valve Actuator Plunger Movement vs Plunger Load at 1200 VDC

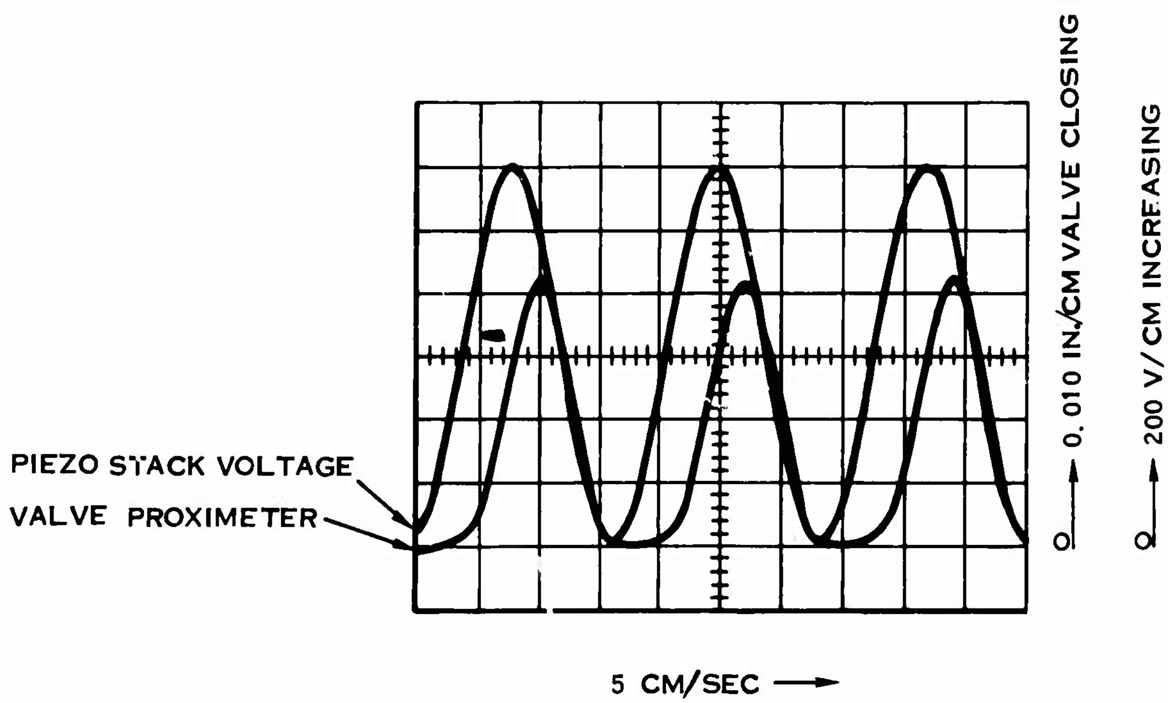

Figure 16. Typical Piezoelectric Valve Actuator Plunger Response to 1200-Volt 60-Hz Sinusoidal Input

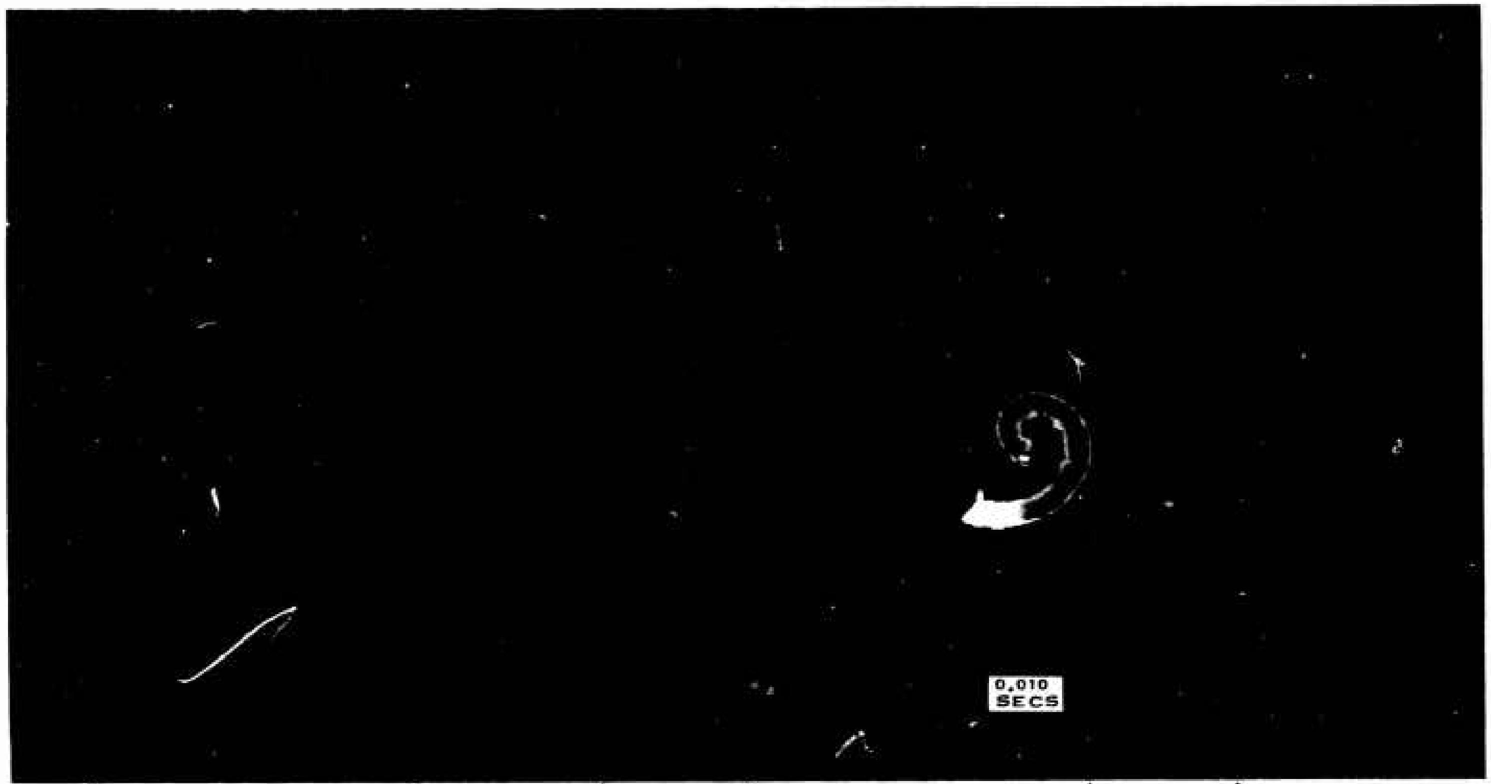

Figure 17. Typical Viscorder Trace-Metering Mode at 30 pps and 50% Pulse Width

Two series of tests at room temperature were attempted, with each one terminated by an electrical/mechanical failure of the piezoelectric actuator. No tests were attempted at the -65°F fuel and ambient or the +135°F fuel and +160°F ambient except a basic rig checkout. A discussion of the results of the two series of tests follows.

Test Series 1

The initial test configuration was installed (see Figure 12) and an exploration of system operation made. A typical visicorder trace is shown in Figure 17. Here valve motion, voltage, inlet pressure, outlet pressure, regulating valve delta P, and fuel flow are shown taken at 30 pulses per second (pps) and 50% pulse width -- the length of time that the voltage was at maximum level. Data was taken with the system operating at maximum flow, 300 psig inlet pressure, and 100 psig discharge pressure in the metering mode.

Valve response is seen as very sharp, lagging input voltage by only a few milliseconds. Excursions in input pressure are less than 50 psig. Average flow is 250 pph.

An attempt was made to get the configuration to operate in the pumping mode but was unsuccessful since the metering piston would not close at 20 to 100 pps and 50% pulse width. Testing was resumed in the metering mode and trial data taken at 20, 30 and 40 pps with pulse widths at 4, 10, 30, 50, 70 and 90%. However, during the course of this test, leakage was observed coming from the area of the high-voltage connector of the actuator. A plot of this data is shown in Figure 18. Data validity is not certain since very shortly after leakage was observed at the electrical connection, the actuator would not accept a voltage signal without breakdown to zero voltage. The breakdown was isolated to the actuator. The unit was removed from the hydraulic housing and returned to the Physics International Company.

Teardown of the unit revealed:

1. The ceramic insulator on the inside of the high-voltage connector had broken, which permitted fluid to leak externally.

2. The beryllium, copper diaphragm providing the seal between the fuel and dielectric fluid was cracked. This permitted test fuel to replace the dielectric fluid surrounding the piezoelectric stack.

3. The crystal stack was coated with a dry black substance that would wipe off easily.

4. Heavy carbon traces were evident across the edges of the discs in two areas.

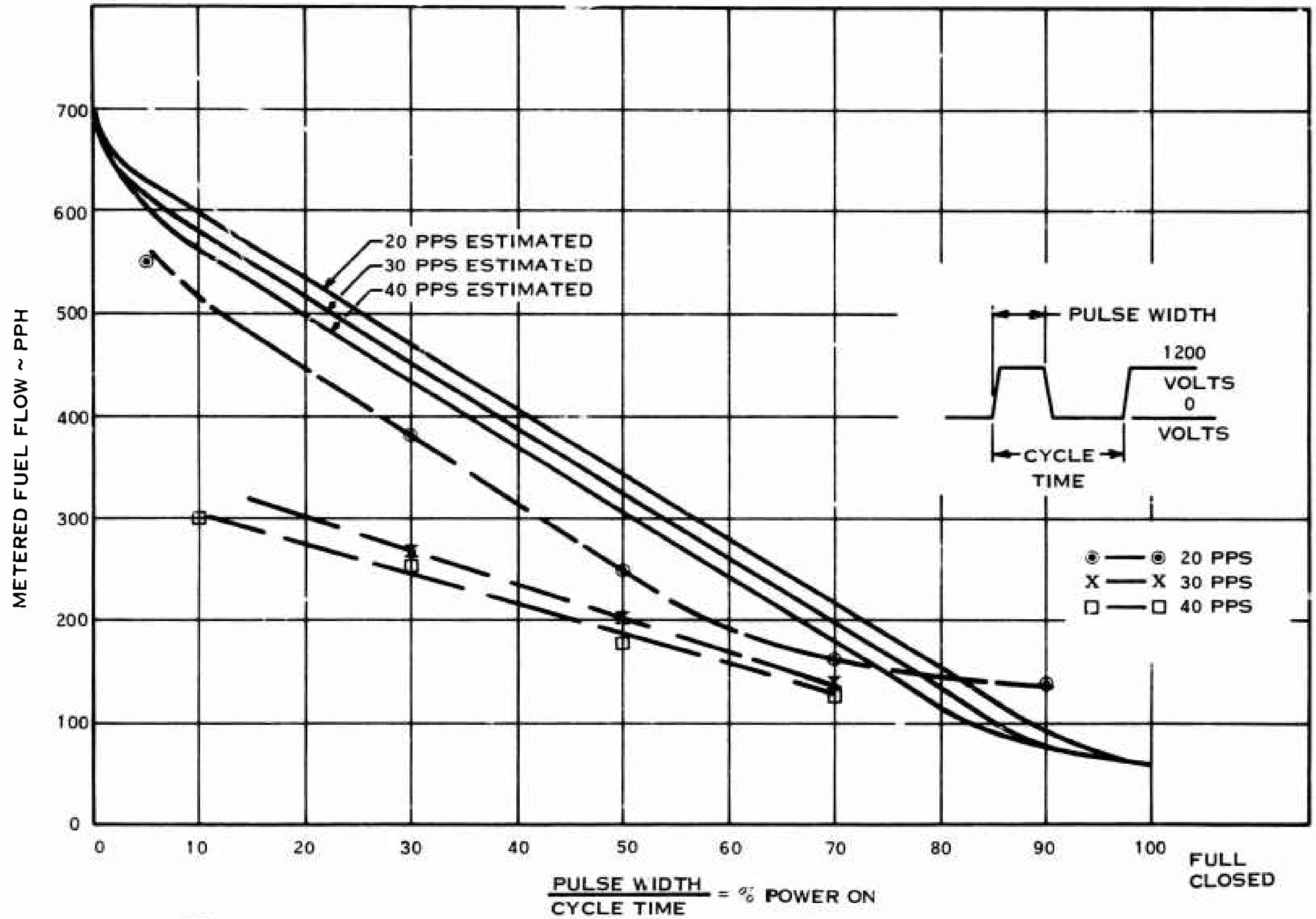

Figure 18. Piezoelectric Pumping Interface - Test Series 1 Performance at Room Temperature

The precise mechanism of the failure can only be surmised, but it would seem certain that this design of piezoelectric stack cannot tolerate fuel as a dielectric fluid. The arcing occurred at electrodes between the stacked discs. Fuel (MIL-F-7024A Type II) replaced the Dow Corning dielectric fluid through the cracked diaphragm. Breakdown of this fuel in the presence of arcing is assumed to be the cause of the black deposit and carbon tracks. External leakage through the ceramic connector was the only clue, prior to the electrical short, that fuel had replaced the dielectric fluid. The failure of the diaphragm could have resulted from a number of causes, such as overstressing, improper heat treatment, or improper assembly.

The unit was rebuilt with a new piezoelectric stack, a new diaphragm with slightly different heat-treat properties, and a redesigned electrical connector with a nylon feedthrough and an elastomeric seal rather than one of a ceramic type. The unit as modified was returned for further tests.

Test Series 2

The repaired actuator was installed on the hydraulic package with the object of completing Phase III tests. A brief test was conducted to confirm operation in the metering mode and performance in the pumping mode explored. These tests were initially monitored on a dual-beam oscilloscope. The metering piston was observed closing at 20 to 100 pps and 50% pulse width. With a 20-psig inlet pressure, pumping to a maximum discharge flow of 125 pounds per hour at 80 psig was achieved for a very short time before erratic operation curtailed operation. Attempts to isolate the cause of the erratic behavior, evidenced by the metering valve's not following the input voltage pulse, ultimately ended in the actuator's not responding to voltage input above 400 volts. Testing was terminated and the actuator disassembled. The diaphragm was again cracked and the stack found shorted in a random pattern. This shorting was again evidenced by carbon traces at the disc interconnections. It was reported that this is symptomatic of having been operated prior to the diaphragm failure without a dielectric medium. The diaphragm showed indications of having been installed off center, which could have resulted in notch sensitivity overstress. The program was terminated and no further evaluation made.

CONCLUSIONS

The test results obtained with this breadboard demonstrator program utilizing a piezoelectric electronic-to-mechanical interface device indicate that the system can operate in a pumping mode to provide the small flows equivalent to starting requirements, and can control fuel flow by pulse-width modulation in a metering mode when operating with a centrifugal fuel pump supply.

The pumping and metering principle of this control concept, with its demonstrated fast response, is sound, but additional work is required in the area of the piezoelectric stack and actuator configuration to uncover and understand the cause of the failures and to establish the required corrective action.

RECOMMENDATIONS

Based on the results obtained from the current demonstration program, it is recommended that work be further pursued on piezoelectric electronic-to-mechanical interface devices as applied to gas turbine engine controls.

The scope of the work should include:

Study, evaluation and tests of the basic piezoelectric stack and amplifying mechanisms to attain reliability in the gas turbine fuel environment.

Implementation of the improved piezoelectric devices on control breadboard systems to permit endurance, environmental and performance tests.

Use of the results of the testing to form a basis for the preliminary design and hardware execution of systems for further tests, including engine tests.

Trade-off analyses of the relative merits of this interface compared to existing state-of-the-art devices.